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The need for better tools to design future CMB experiments

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1 Introduction

This white paper addresses key challenges for the design of next-decade Cosmic Microwave Background (CMB) experiments, and for assessing their capability to extract cosmological information from CMB polarization. We focus here on the challenges posed by foreground emission, CMB lensing, and instrumental systematics to detect the signal that arises from gravitational waves sourced by inflation and parameterized by r, at the level of $r \sim 10^{-3}$ or lower, as proposed for future observational efforts. We argue that more accurate and robust analysis and simulation tools are required for these experiments to realize their promise.

We are optimistic that the capability to simulate the joint impact of foregrounds, CMB lensing, and systematics can be developed to the level necessary to support the design of a space mission at $r \sim 10^{-4}$ in a few years. We make the case here for supporting such work. Although ground-based efforts present additional challenges (e.g., atmosphere, ground pickup), which are not addressed here, they would also benefit from these improved simulation capabilities.

The expected inflationary signal has peaks at low multipoles, $\ell \sim 8$, and mid-multipoles $\ell \sim 80$. Measurements at low ℓ require near full-sky coverage, for which foreground are $\sim$100 times larger in amplitude than the signal at 75 GHz (for 60% sky). Although measurements at the mid-multipoles can be initially conducted on smaller patches of the sky, for which the foregrounds are $\sim$10 times larger than the signal, this comes with a penalty on the cosmic variance error from the signal from lensing of the CMB photons, brighter than target inflationary B-modes by a factor of 3 (assuming $r \sim 10^{-3}$) or more.

Hence, improvements in r between 1 and 2 orders of magnitude with respect to the current upper limit $r < 0.07$ (95%) will require improvements in foreground separation, CMB de-lensing, and systematics by similar or greater factors. No existing or proposed experiment has demonstrated the capability to address all of these issues simultaneously at the required level. Control of foregrounds and systematics is also important for attaining cosmic-variance-limited measurements of the optical depth to reionization, τ. The large-scale E-modes that encode most of the relevant information are below the foregrounds at $\ell < 10$, and systematics need to be controlled on the largest angular scales at a matching level. Furthermore, foregrounds play an important role in recovering the spectral distortions signals in the CMB. [1]

2 ThinK- the philosophy in going from scientific goals to the mission

In designing future missions, the fundamental question is what measurements must be made in order to address the science goals? Few missions address only a single goal, and hardware designed to do one thing well invariably does many things. So the question becomes what measurements that we need to make drive the design of the hardware. In effect, what measurements are the most difficult to make, or require the greatest capability?

[1] This whitepaper is a summary of the report from the KISS workshop (Rocha et al., 2019) 'Designing future CMB experiments', held on March 19–23, 2018, at Caltech, Pasadena, CA, USA. The report (in prep.) will appear here: http://kiss.caltech.edu/workshops/fCMB/fCMB.html

As we have discussed, determination of r, is particularly hard. It requires measurement of fluctuations in polarization on large angular scales at extremely low levels, which **WMAP** and Planck have demonstrated is the hardest of all anisotropy measurements to make, with the added complication that we do not know in advance at what level the fluctuations will appear. There are many models of inflation, and many predictions of the size of r over many orders of magnitude (see Figure 1). Since we do not know the level of gravitational-wave-induced B-mode polarization in the reionization and recombination peaks, we simply cannot specify how well we must measure the sky to extract most of the relevant information.

In designing experiments, then, we suggest the following two principles:

- **Take big steps, but not too big.** Steps into the unknown carry significant uncertainty. A distant goal is more effectively reached in two steps, with learning and correction after the first incorporated into the second, than in one giant step. The kind of experiments that we are discussing are expensive, whether on the ground or in space. Small, merely incremental steps do not justify the cost. But too big steps risk going astray. It's a matter of judgment, but hardheaded ambition rather than untethered dreaming should prevail.

- **Understand the real limitations of the measurements.** For CMB experiments, noise has always been a major issue, and so it will remain. However, systematic errors ("systematics") have been the limitation for many experiments, from early attempts to measure the Solar dipole to the 2014 claim that primordial B-mode fluctuations were measured, when the fluctuations were, in fact, mostly due to polarized Galactic dust emission.

The critical point is that the limitation of future experiments will be some combination of foregrounds and systematics. Since in principle instrumental systematics can be reduced, but foregrounds cannot, it is inevitable that foregrounds will set the ultimate limit on how well the CMB can be measured.

It is straightforward to calculate how well B- and E-mode power spectra must be measured to determine r to a certain level. Straightforward, although not entirely simple: it matters, for example, whether one is determining an upper limit, or measuring a constrained value. But the complications are far greater in trying to predict the effects of foregrounds and systematics. These can be estimated before launch, but they can only be known for sure from the data themselves. The hard — very hard — part is to separate them from one another, so that something can be done about them. Only if a certain feature or pattern in the data can be traced to a particular instrumental behavior, known before launch or discovered in flight, and simulated with confidence, is it possible to say that it is understood, and to do something about it. Correlation is not good enough. Systematic effects can be degenerate, or nearly so, where certain combinations of systematics mimic each other. The further along in the analysis, the more this is true. At the power spectrum level, separation of systematics from each other is essentially impossible. At the map level, the situation is better, because the two-dimensional nature of the data provides many more clues. Other problems, obviously including time-dependent ones, can only be adequately understood at the time-ordered-data level.

Accurate quantitative assessments will require high fidelity simulations, but we can make some crude estimates. With τ (the optical depth to reionization) of about 0.06, the reionization bump ($2 \leq \ell \leq 12$) in the B-mode power spectrum would be at a level of about $1\,\mathrm{nK}^2$ for $r \sim 10^{-4}$. The rms brightness temperature of B-mode fluctuations on a $40'$ scale at about 200 GHz is about 1 nK as well, a factor of 20 or so below the level of ***synchrotron*** fluctuations at that frequency over 70% of the sky, and a factor of ~ 2000 below the level of ***dust*** fluctuations. Errors in the final Planck maps, after a decade of processing, were of order $1\,\mu$K on a $1°$ scale, and supported an upper limit on r of 0.08. To reach $r = 0.0001$, one might calculate that maps would have to be $\sqrt{800}$ better, or in the 30 nK range. Given that the combined effects of residual foregrounds and systematics are likely to get harder to disentangle at lower levels, it is not hard to believe that map errors at a level of ≤ 10 nK are about the largest that can be tolerated. We summarize this level by saying "think nK", or Thi**nK**.

3 The Science Cases

The science case for future CMB experiments has been clearly laid out in Astro2020 Science whitepapers (e.g., Shandera et al., 2019; Chluba et al., 2019). We list here a few key elements. **(a) Inflationary models** for the origin of cosmological perturbations: These models postulate that the sources of gravitational waves in the early universe are vacuum (quantum) fluctuations from Inflation (an era of accelerated expansion in the early universe). These models have succeeded in resolving the homogeneity, isotropy, flatness and monopole problems, and the puzzle of explaining how the universe obtained a nearly scale-invariant spectrum of density variations that extend to super-horizon scales. Inflation requires exponentially fine-tuned initial conditions to initiate a sufficiently long period of accelerated expansion. Figure 1 shows the predictions for the tensor-to-scalar ratio, r, and the scalar spectral index, n_s, of several Inflationary models along with constraints from Planck/BK2 and forecasts for PICO (Hanany et al., 2019). **(b) Non-inflationary models** for the origin of cosmological perturbations: An example of non-Inflationary models are the Cyclic models (see Shandera et al. 2019 and references therein for other models). Cyclic models of the universe provide an explanation for the homogeneity and flatness of the universe and the cosmic generation of a nearly scale-invariant gaussian spectrum of density perturbations while avoiding any kind of initial condition or multiverse problems. Inflationary expansion is replaced by ekpyrotic (ultra-slow) contraction and the big bang is replaced by a transition from contraction to expansion, sometimes referred to as a "bounce." The resulting cosmology not only resolves

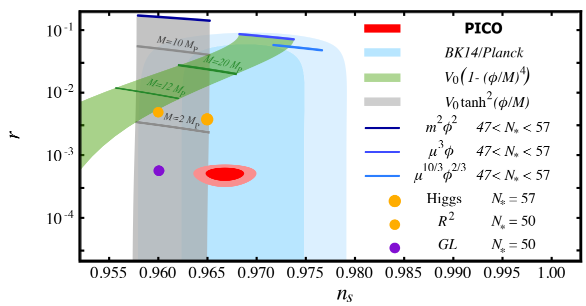

Figure 1: Current 1σ and 2σ as limits on r and n_s (cyan) and forecasted constraints for a fiducial model with $r = 0.0005$ for PICO, together with predictions for selected models of inflation. Adapted from Hanany et al. (2019).

the standard cosmological conundra, but also implies the ***absence of B-modes,*** evades the cosmological singularity problem and resolves the entropy problem of earlier cyclic models. Inflationary and cyclic scenarios have important distinctions. For example, in an inflationary multiverse, a Hubble-sized patch of space like we observe today might be spatially flat, but it can just as well be open or closed. In the cyclic scenario, there is no option: the patch must be spatially flat, period. And the same applies to other features of both the Inflationary and cyclic models.

(c) CMB spectral distortions:

The sky-averaged CMB spectrum is known to be extremely close to a perfect blackbody at a temperature (Fixsen et al., 1996) $T_0 = 2.7255 \pm 0.0006$ K, with possible distortions limited to parts in 10^5. Given the uncertain prospects for detecting a primordial B-mode signal from inflation, it is relevant to consider complementary approaches that are capable of yielding unique information on the primordial universe, directly probing unprecedentedly early epochs back to the epoch when the cosmic blackbody radiation originated. Sources of spectral distortion arise in the pre-recombination and post-recombination epochs where spectral distortions emerge as a combination (Chluba, 2016) of late epoch y-distortions (Zeldovich and Sunyaev, 1969) and early epoch μ-distortions (Sunyaev and Zeldovich, 1970) in the standard ΛCDM model. Figure 2 shows these spectral distortions versus frequency and the proposed PIXIE sensitivity (Kogut et al., 2016; Desjacques et al., 2015).

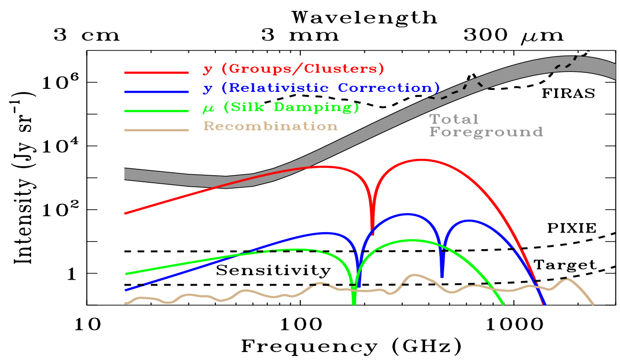

Figure 2: Spectral distortions vs frequency, infrared foregrounds, the standard and relativistic y and μ spectral distortions and the hydrogen and helium recombination lines; the proposed PIXIE sensitivity and the target sensitivity needed for a guaranteed minimal science return. Adapted from Desjacques et al. (2015).

4 A CMB Program: Space vs Ground Complementarity

Historically, major steps in CMB observations have been made from the ground, from balloons, and from space. What of the future? The answer depends on the level of accuracy that must be achieved.

The advantages of space are full coverage of the frequency spectrum, full coverage of the sky, freedom from systematic errors associated with the Earth's atmosphere or surface, and stability. The advantages of the ground are accessibility and cost.

Figure 3 shows typical atmospheric transmission from a high, dry site such as the South Pole or the Atacama plateau in Chile. Strong atmospheric absorption features limit ground-based observations to frequencies below 45 GHz or to relatively narrow "windows" centered at 90, 150, and 250 GHz. Within these windows, atmospheric emission is bright but largely unpolarized; its principal effect is increased noise coupled with restrictions on effective scan strategies. To quantify the effect of the noise, the rule of thumb among CMB experimentalists is that one detector in space is worth 100 detectors on the ground. Moreover, comparison of Figure 3 with Figure 4 shows that the atmosphere is essentially opaque in the important minimum foreground frequency band.

Space offers particular advantages for measurements on the largest angular scales. Free from diurnal temperature variation, space platforms have demonstrated mK stability on time spans of months to years, reducing effects of long-term calibration drifts. With no terrain to induce position-dependent ground pickup, offset drifts are correspondingly minimized. Orbital observatories have minimal constraints on pointing pitch or roll angle, and can readily rotate about the beam axis to generate full parallactic angle coverage within each sky pixel. These effects combine to control systematic errors, which can otherwise dominate over instrument white noise on the largest angular scales.

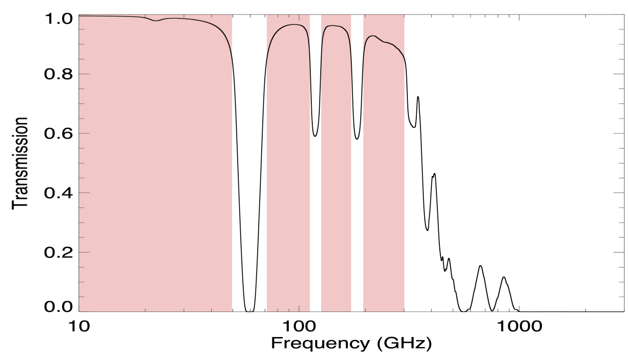

Figure 3: Atmospheric transmission vs frequency from a high, dry site (South Pole or the Atacama plateau). Pink bands show the primary windows to observe the CMB. Measurements outside these windows are impossible from the ground.

Space platforms are the only viable option to measure distortions from the CMB blackbody spectrum (§3). Distortions from hot gas in groups and clusters are expected at the 100 nK level, with distortions from the dissipation of primordial density perturbations present at nK levels. Separating these signals from competing foreground emission requires continuous spectra calibrated to a common standard across several octaves in frequency. The resulting long integration times outside the available atmospheric windows requires a space mission.

On the other hand, the 5–10-m telescopes desirable for studying neutrinos and secondary anisotropies are much more easily obtained on the ground than in space. Ground-based platforms are also more flexible than space missions. Multiple platforms operating at multiple locations allow robust cross-checking of different detector technologies and observing strategies. Simple access to ground-based observatories allows frequent incremental upgrades. Ground-based instruments develop and use cutting-edge technologies, while the longer development cycle and lower risk tolerance for space missions can leave such missions a decade behind ground-based state of the art. The shorter development time and higher risk tolerance for ground-based missions allows quick reaction to new discoveries.

To summarize, for $r \geq 10^{-3}$ from the recombination bump ($\ell > 30$), for neutrinos and secondary anisotropies, observations from the ground may be possible and important. For $r < 10^{-3}$, especially for $\ell < 30$, and for spectral measurements, space is the only option.

5 Systematics

As instrumental sensitivities approach the nK threshold, instrument design must become correspondingly robust against systematic effects at that level. Although instrumental effects are by their nature instrument-specific, a robust design will include multiple lines of defense:

- **Eliminate:** Differential measurements are a powerful tool to eliminate broad classes of systematic errors. By canceling common-mode signals, differential techniques prevent these signals from sourcing systematic error. A common example is the differential comparison of signals from independent beams on the sky, which rejects emission from the CMB monopole and (for co-pointed beams) unpolarized anisotropy." Beam ellipticity can couple to local gradients in the sky brightness to mimic sky polarization. Differential measurements remove this common-mode signal component, eliminating temperature–polarization coupling to first order.

- **Mitigate:** Null measurements suppress systematic effects by reducing the amplitude of the underlying source terms. For example, absorption and emission from optical surfaces within an instrument can impart instrumental polarization to modulate or mimic true sky polarization. Instrumental polarization depends on the temperature difference between the sky and the optical surfaces within the instrument. Maintaining the instrument within a few mK of the sky temperature suppresses instrumental polarization by 3–5 orders of magnitude compared to optics maintained at room temperature.

- **Modulate:** Modulation imparts a distinctive time-dependent signature on desired sky signals to distinguish them from instrumental effects that do not share the same time dependence. Polarization modulation is a common example. A rotating half-wave plate placed as the first optical element within an instrument causes the plane of polarization from sky signals to rotate at twice the frequency of the wave plate. Synchronous demodulation at twice the rotation frequency efficiently separates polarized sky signals from fixed instrumental polarization (constant in time) or even spurious signals from the rotator drive itself (typically occuring at the rotation frequency). Sufficiently rapid modulation also mitigates slow drifts or $1/f$ noise, forcing the sky signal to frequencies above the $1/f$ knee.

- **Calculate:** Improvements in raw sensitivity require corresponding improvements in the modeling of instrumental effects. Reaching nK sensitivity and beyond demands calculation of effects beyond first order in perturbations. To return to the example of beam ellipticity above, we see that differential beam subtraction eliminates temperature-polarization coupling from beam ellipticity to first order. At second order, however, the ***differential*** beam ellipticity still couples with unpolarized gradients on the sky to mimic a polarized sky signal. Similarly, the cross-polar response of the instrument beam pattern can couple with a transmissive half-wave plate to create $E \rightarrow B$ polarization mixing, again at second order. First-order suppression is not necessarily sufficient to reach nK sensitivity; next-generation CMB missions must calculate systematic error signals to higher order to ensure that errors are sufficiently suppressed.

As raw sensitivity improves, all possible techniques will be required to reduce systematics to levels below the noise. Presently available tools are not reliable at the nK level required by the most ambitious future experiments. We identify development of improved tools as a critical element in the CMB program, and ask for a recommendation of support for such development.

6 Foregrounds

The *Planck* mission has demonstrated that Galactic emission will be the dominant foreground, especially at large angular scales. The principal diffuse Galactic foregrounds in polarization are dust emission, which dominates at high frequencies, and synchrotron emission, which dominates at low frequencies (see Figure 4). However, other diffuse foregrounds are known to contribute significantly in total intensity and may be relevant in polarization as well, particularly at the sensitivity levels of next generation missions. These other emission mechanisms are: free-free emission, anomalous microwave emission (AME), line emission from interstellar gas (particularly the CO rotational lines), the Zodiacal Light at far-infrared frequencies, and the Cosmic Infrared Background (CIB).

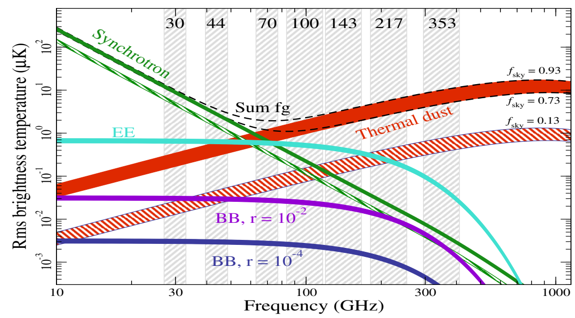

Figure 4: Brightness temperature rms as a function of frequency and astrophysical component for polarization. Based on figure 51 from Planck Collaboration X (2016)

Known physical complexities in foreground emission not encapsulated by simple parametric models, such as line of sight averaging and grain alignment, should be quantified in terms of their effect on foreground subtraction. Models have been developed to describe the spatial morphology and frequency dependence of many of these foregrounds, enabling high fidelity component separation at current noise levels. A key question for a future CMB mission is the extent to which the parameterizations currently employed will describe the various foregrounds at the accuracy demanded by future missions. This presents something of a conundrum–the presence of new subtleties in foreground emission may drive choices in instrument design and data analysis, but they can be truly characterized only by making the measurements.

We postulate that there are three broad paths for bringing theory, data, and simulations to bear on this problem and thereby improving forecasting as well as informing the development of instrument designs and component separation algorithms (Rocha et al. 2019).

- **Connect Physical Foreground Models to Uncertainties in Foreground Subtraction**: The physics of the various emission mechanisms that constitute the CMB foregrounds is rich and complex. Known physical complexities in foreground emission not encapsulated by simple parametric models, such as line-of-sight averaging and grain alignment, should be quantified in terms of their effect on foreground subtraction. Detailed calculations should be made of the expected levels of polarization emission from free-free, CO, and Zodiacal Light. Empirical constraints on the polarization properties of these emission mechanisms should be established using existing data.

- **Develop More Sophisticated Simulations That Capture Important Known Complications of Foreground Emission**: The efficacy of foreground mitigation strategies, whether in instrument design or data analysis, should be assessed against simulations that reflect realistic levels of foreground complexity. Further development of existing sky models that use Galactic observations to constrain the spatial statistics of the various foregrounds (eg., the Planck Sky Model (Delabrouille et al., 2013) and the Python Sky Model (Thorne et al., 2017)) should be pursued. In particular, generating non-Gaussian realizations of foreground amplitudes at small multipoles would be valuable. The use of Magnetohydrodynamic simulations, which can incorporate many of the relevant complexities in a natural, physically-motivated way, to generate mock microwave skies should be developed further (e.g., Kritsuk et al., 2018; Kim et al., 2019).

- **Explore How Existing and Upcoming Ancillary Datasets Can Be Incorporated in Component Separation**: The data landscape at the time of the next space mission will include detailed observations of the three dimensional, magnetized interstellar medium as well as catalogs of extragalactic sources at relevant frequencies. Assembling a comprehensive, multi-frequency picture of the 3D ISM is an active area of research, e.g., the IMAGINE Consortium (Boulanger et al., 2018) [2] and Cosmoglobe[3], which will play an important role in informing and validating CMB component separation. Ancillary data from sub-orbital experiments can also play a crucial, direct role by extending frequency coverage to both higher and lower frequencies that cannot be realized on a single space mission.

7 Lensing

The CMB is gravitationally lensed by large-scale structure as it propagates across the 14 Gpc (comoving) distance from recombination to the present. Lensing remaps the temperature and polarized surface brightness, distorting our view of the primary CMB fluctuations. This is both a blessing and a challenge. The distortions due to lensing introduce very specific non-Gaussian statistics to the lensed CMB, which can be measured to extract information on the large-scale clustering of matter at intermediate redshifts that is difficult to access by other means. However, lensing also blurs our view of the infant universe. In particular, lensing converts E-mode polarization into B-modes, confusing searches for the B-mode signal from primordial gravitational waves expected from inflation.

Here, we focus on the issue of mitigating the effect of lensing on searches for degree-scale primordial B-mode polarization. The B-modes produced by lensing have an almost white-noise angular power spectrum on large scales, equivalent to an additional map-level noise of $5\,\mu$K arcmin. These have now been measured by the BICEP/Keck Array experiments (BICEP2 Collaboration and Keck Array Collaboration, 2018), and on smaller scales by SPTPol (Keisler et al., 2015), ACTPol (Louis et al., 2017) and POLARBEAR (Ade et al., 2017). If the tensor-to-scalar ratio $r < 0.01$, the signal power is below that from lensing at multipoles $l > 10$; only the large-scale signal from reionization exceeds lensing. However, the expected lensing power can already be predicted at the percent level, and subtracting this from the measured power allows one to access primordial gravitational waves with $r \ll 0.01$. Such subtraction does not remove the sample variance of the lensing B-modes, though, and

[2] https://www.astro.ru.nl/imagine/imagineprojects.html
[3] http://cosmoglobe.uio.no

Table 1: Impact of lensing on constraints on the tensor-to-scalar ratio r for a survey covering 70 % of the sky, with polarization sensitivity $1\,\mu$K arcmin (after foreground cleaning). For each model, the 1σ errors on r are shown using only B-mode multipoles with $\ell < 30$ (i.e., the signal from reionization) and $\ell > 30$ (the signal from recombination) and different assumptions about the level of delensing. The parameter A_L describes the fraction of residual lensing B-mode power assumed after delensing, so that $A_L = 1$ corresponds to no delensing, $A_L = 0$ to perfect delensing, and, for example, $A_L = 0.2$ to removing 80 % of the lensing power.

	$10^4 \times \sigma(r)$							
	$A_L = 1$		$A_L = 0.5$		$A_L = 0.2$		$A_L = 0$	
Model	$\ell < 30$	$\ell > 30$	$\ell < 30$	$\ell > 30$	$\ell < 30$	$\ell > 30$	$\ell < 30$	$\ell > 30$
$r = 0$	0.72	4.3	0.38	2.2	0.17	1.0	0.030	0.18
$r = 4 \times 10^{-3}$	7.2	5.0	5.2	2.9	3.6	1.6	2.5	0.72
$r = 1 \times 10^{-2}$	11	6.0	8.8	3.9	7.0	2.5	5.7	1.3

if the effective instrument sensitivity (after removing Galactic foregrounds) is significantly below $5\,\mu$K arcmin lensing can limit constraints on r.

We illustrate the impact of lensing on inflation constraints in Table 1. We see from Table 1 that at a sensitivity of $1\,\mu$K arcmin, the detection threshold for r is strongly limited by lensing. Fortunately, it is possible to remove partially the lens-induced B-modes in a process known as delensing (Kesden et al., 2002; Knox and Song, 2002).

Delensing of B-modes has recently been demonstrated in practice (Planck Collaboration VIII, 2019; Manzotti et al., 2017), although with current noise levels these analyses have not led to improved inflationary constraints. However, for forthcoming ground-based experiments delensing will be essential to exploit fully their improved instrument sensitivities. These surveys will provide an opportunity to refine our delensing algorithms to deal with real-world issues such as variable depth observations, and to understand better the interaction between Galactic foreground removal and delensing. Biases, for example due to squeezed configurations of the 4-point function of polarized foregrounds, are currently poorly understood due to a lack of high-quality data. Significant further development of techniques will be required to achieve the necessary accuracy of delensing for a space mission aiming for a level of r of 10^{-4}. In addition, simulations of the turbulent, magnetized interstellar medium, which faithfully capture the non-Gaussian statistics over a sufficient dynamic range, can also play an important role here.

8 Statistical methods for large scale polarization

A major challenge facing future polarization measurements of the CMB is an accurate quantification of uncertainty in *cosmological parameters* in the presence of foregrounds, CMB lensing, and instrumental systematics. As stated before, current methods are not reliable at the nanokelvin level required for $r \sim 10^{-4}$. Many different approaches have been proposed in the literature in order to perform component separation. (see eg. (see Planck Collaboration XII, 2014; Planck Collaboration IX, 2016; Planck Collaboration IV, 2019; Rocha et al., 2019). However, it is not clear that these methods will suffice for future experiments, given the uncertainties in the knowledge of the foreground emission and the required nK sensitivity. Within this context, tailored statistical methods to analyse the large scale polarization signal are needed to obtain a robust and unbiased constraint of the tensor-to-scalar ratio r and the reionization optical depth τ parameters. Exampes are: (a) Gaussian Likelihood function computed exactly in pixel space (Gorski et al., 1994; Slosar et al., 2004; Page et al., 2007; Bennett, 2013). Although optimal, this approach relies on the precise reconstruction of the noise matrix in pixel space which can be extremely hard to achieve when systematics, related to the instrument, the scanning strategy and the residual foregrounds, dominate over noise. New methods must therefore be explored to solve this critical issue. (b) The analysis of the Planck HFI 100 GHz and 143 GHz large scale E-modes polarization data to constrain τ (Planck Collaboration Int. XLVI, 2016; Planck Collaboration Int. XLVII, 2016) represented a first step in this direction. (c) A possible solution to the problem is given by defining the likelihood in the harmonic space and using the CMB power spectra calculated from the cross correlation of different frequencies and/or data splits as input data (Mangilli et al., 2015), instead of maps as in the pixel based likelihood method. This has the advantage of greatly reducing the impact of uncorrelated residual systematics which are different at each frequency and therefore do not bias the cross-spectra. (d) One important method for joint CMB and foreground reconstruction is global Bayesian analysis. In this framework, the user must first define a parametric model that accounts for cosmological, astrophysical, and instrumental parameters. The goal is then to map out the full joint posterior distribution. It is possible to sample from this posterior distribution through Gibbs sampling. Commander is one specific implementation of this approach that was developed for, and used extensively, by the Planck collaboration. At least three conceptually different methods of constraining cosmological parameters based on Gibbs sampling have been proposed in the literature so far (the method adopted for the Planck analysis called the Blackwell-Rao estimator; and two other approaches (see Gjerløw et al., 2013; Racine et al., 2016). Further development of these promising statistical approaches is crucial for future experiments with nK sensitivity.

The simulator and analysis pipelines inherited from Planck data analysis represent great progress in accounting properly for the foreground model uncertainties and instrument systematics. However, the inevitable cross-talk between the foregrounds and the instrument systematics, which can bias the estimation of cosmological parameters, is not yet implemented there, and neither foreground nor instrument systematics can yet be simulated or analyzed at the nanokelvin level.

9 Concluding remarks

We conclude by stating that significant work is required. But we are confident that with a few years of efforts, the requisite level of accuracy can be achieved, and a space mission able to extract the full range of information provided by the Universe at the nanokelvin level can be designed, built, and flown.

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